A "teach-in" of the basics of steel production and decarbonization for the policy orientated

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Outline of the next up to 2 hours

• How steel is made today, and what parts of the process do the GHGs come from?
• Why we need net-zero GHG steel
• The seven technical pathways to net-zero steel
• Our methodology: A series of geospatially detailed, plant level global transitions to net zero for steel, including projections of demand, evolving secondary recycled and new primary production
• Some key global and country results
• Some important details on how steel emissions are measured – there are three main ways.
• Global policy implications
There are four high level steps to steel production: raw material preparation, iron making, steel making, and structural forming.

**Figure 1.2 Main steel production pathways and material flows in 2019**

- **Raw material production**: Coke oven, Sinter plant, Pellet plant, Lime fluxes, Scrap, Collection and sorting.
- **Ironmaking**: Blast furnace, DRI furnace, Smelting reduction furnace, Open-hearth furnace, Electric furnace.
- **Steelmaking**: Basic oxygen furnace, Electric furnace.
- **Structural forming**: A.k.a “reduction”

**“Longs & flats”**
How steel is mostly made today

~70% of steel made in 2020

Source: Babich 2019

~25% of steel made in 2020

“Longs & flats”

Source: Wang et al 2021

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Upshot from our 2019 database building; the vast majority of steel capacity is in Asia, and especially China. And much of it was built 1995-2015, especially 2000-2010. On a 25 year furnace relining schedule, it’s up for renewal 2025-2035.
Seaborne trade in iron & steel raw materials

Source: Liu et al 2021 “Are the environmental impacts, resource flows and economic benefits proportional? Analysis of key global trade routes based on the steel life cycle” – Ecoglogical Indicators
Map of volume & quality of higher grade ores globally
Metallurgical coal trade

Overall export 2019

2018 2019

This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.
BF-BOFs have stopped getting more efficient

**Figure 13.3** Evolution of reducing agents consumption in the German blast furnaces.
Enter direct reduction, the other 5%.

With clean electricity, a best available DRI dramatically reduces energy needs and reduced emissions from 1.8-2.2 tCO$_2$e per tonne steel to 0.7 tCO$_2$e/t.

Also, DRI iron making can be physically separated from steel making.
What steel costs when all input markets are humming along at cost + normal profits ...
Where do the emissions come from?

1) Separation of iron from oxygen in iron ore ($\text{Fe}_3\text{O}_4/\text{Fe}_2\text{O}_3$),
   \[ \text{C} + \text{O} = \text{CO} \quad \text{&} \quad \text{CO} + \text{O} = \text{CO}_2 \]
2) Getting the carbon level right, and adding other metals to make steel

Processes included in study boundary

80% electrified already
Historical GHGs due to various steel technologies

Source: Wang et al 2021
Why is net-zero iron & steel essential?

- Steel is essential for modern civilization for energy, water, sanitary, and transport infrastructure as well as vehicles and machinery.
- Steel is currently very GHG intensive, and 6-10% of global energy combustion & process CO₂ emissions, depending how measured.

The cost of negative emissions BECCS or DACCS offsets will be ~$100-300/t CO₂e, if available.
How to eliminate reduction & smelting emissions

• Less demand, more material efficiency
• More recycling. Depends on supply of reasonable quality scrap and a network to gather it + DRI sweetening (TRL 9)
• BF-BOF with 90%+ Carbon capture and storage, possibly with biomass TRL 5* (2030?)
• Advanced smelting with CCS (not shown, TRL 7 ... but dormant?)
• Syngas ($H_2$+CO) based DRI EAF with concentrated flow CCS TRL 9*. Replaceable with 100% hydrogen
• Green hydrogen DRI EAF TRL 5-7+ & moving fast (2026-’30?)
• Molten oxide or aqueous oxide electrolysis TRL 4 (2035+? BM says late 2020s) Wild card given transformative anode development needs and ++on-demand power draw

* Hydrogen blending would allow partial reductions
A note on DRI reactors and iron ore quality. Most of the market is structured to supply lower grade, lower cost ores for BFs (~55-62%). Current DR requires >66% - while an issue, there’s actually lots of long run supply and several companies are working means to use all ore types, either through concentration or use of poorer quality fines (e.g., Calix “Zesty”, Voestalpine “Hyfor”, etc.)

The core question is whether suppliers have the investment confidence necessary to bring sufficiently concentrated DR grade ore to market in time.
Some facility level netzero pathways to green steel
High level simulation methodology

• **Initial database:** We begin with a global dataset of existing steel plants >1Mt in 2019 provided by the Global Energy Monitor, and added from other data sources to build up a full set. These last 17-25+ years between furnace relinings.
Upshot from our 2019 database building; the vast majority of steel capacity is in Asia, and especially China. And much of it was built 1995-2015, especially 2000-2010. On a 25 furnace relining schedule, it’s up for renewal 2025-2035.
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• **Demand**, based on patterns in long term development needs, is forecast based on a global evolution towards 200, 250 and 300 kg per capita in 2080
We ran 200, 250 and 300, leading to 1.9, 2.2 and 2.5 Gt steel per year in 2050. Middle case roughly corresponds to IEA NZE.
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• **Demand**, based on patterns in long term development needs, is forecast based on a global evolution towards 200, 250 and 300 kg per capita in 2080

• **Recycled production** is preferred because it’s cheaper, but is limited by scrap availability. Based on the literature, global scrap availability is forecasted at ~1.2 Gt in 2050, with ~83% usability. The model assumes for 133 countries that forecast scrap supply will be equal to scrap EAF production by 2050 (61 countries with currently no known EAF production become producers)

• **For primary facilities**, working with the premise that steel makers would prefer to keep using existing sites if possible, we use the following algorithm
Is the current facility near CCS geology, or an industrial cluster with a CO₂ pipeline?

Is there potential excess hydropower, nuclear, wind or solar within transmission distance?

Is there a political preference against CCS?

Is there excess resources of biomass available?

Has post combustion CCS been mastered? (2030)

Is there a tech or political preference for retaining BFBOFs

Has advance smelting been mastered?

90% capture BF-BOF newbuild with CCS is an option in 2030

BF-BOF or DRI Biomass with CCS is an option

Green iron imports with an EAF is an option

Blue hydrogen/syngas DRI EAF with CCS is an option in 2025

Green hydrogen DRI with an EAF is an option in 2028

Done using annual 3.5 kW per meter² per day as the proxy and list of countries with excess hydropower

Done with maximum 100, 200 and 300 km pipelines to the nearest CO₂ reservoir

*with the exception of Germany
But what about cost per tonne? It very much depends on assumed electricity & CCS costs, and carbon pricing level.

Our estimates are based on clean electricity at $0.06 per kWh falling to $0.015. We see initial 20% cost increases with hydrogen DRI EAF, assuming dedicated access to new solar & wind builds, but by 2050 it is cheaper than CCS and only slightly more than BFBOFs today.

The upshot? If initially higher costs can be passed through to end-users using lead markets (with <2% extra costs), then the difference is not relevant. The technology choice will be mostly geographic & political. BFBOFs are known, but HDRI will likely eventually be cheaper including carbon costs.
Global results—medium demand, 200km of CO$_2$ pipelines available
In the medium demand, 200km case, as time passes ...

- Red BF-BOFs gradually disappear
- Yellow EAFs gradually double
- Various shades of light green syngas DRI EAFs with CCS, hydrogen DRI EAF and BFBOFs with CCS arrive
Pipeline availability, e.g., through an industrial cluster in northeast China, is critical to use of CCS, but not critical to decarbonization of steel.

The km distances are from existing steel production sites to the centroid of known potential CO₂ disposal sites from the Oil & Gas Climate Initiative database.
The other big sensitivity – asset renewal timetable

- The most emitting parts are sintering, reduction (BF, DRI) and smelting (BOF, EAF). The renovation schedule for these components matter.
- IEA provides 25 & 40 years as brackets. Vogl et al (2021) recently estimated 17 years as the life between renovations.
- Anything slower than 27-28 years will prevent net-zero without early retirement.
GHG intensity benchmarks
All, primary and secondary facilities

~1.9 tonne CO₂e per tonne steel in 2020, primary & secondary, 2.1 t/t for primary, 0.14 t/t for secondary

~1.1 tonne CO₂e per tonne steel by 2030, primary & secondary, 1.4 t/t for primary, 0.13* t/t for secondary

~0.15 tonne CO₂e per tonne steel by 2050, primary & secondary, 0.17 t/t for primary, 0.13* t/t for secondary

Our stock turnover was determined by a 25 year retrofit cycle, the GEM database age data, and probabilistic estimate for facilities of unknown age – it’s relatively fast compared to the IEA, which has more remnant emissions.

*Work to be done increasing ambition for EAF GHG intensities
We, the IEA, and Worldsteel all measure steel GHG intensity slightly differently. What are the key differences that matter?

- We include all GHGs from all fuels that enter the facility, without credit for sales
- We don’t credit for offsite electricity sales (WS does)
- We don’t credit for offgas or heat sales (WS & IEA do)
- We don’t include GHGs from purchased electricity (WS does), assuming system electricity GHGs are supposed to go to zero.
- Our system is designed for primary process replacement and elec->zero GHGs.
Global production by large producing region
The global picture, and the export opportunity

- About 200 Mt per year of new production could occur anywhere there is access to iron ore, inexpensive clean electricity, or access to CCS geology.
- The big potential exporters are Australia, Brazil, Russia, South Africa, Canada, Guinea...

Where the iron ore is...
Other possibilities –
Thinking bigger about reorganizing supply chains

• We currently make primary iron and steel near coal and iron ore and move it where it’s needed; with hydrogen DRI we can make it near iron ore, cheap clean electricity (green), or cheap methane and CCS (blue), and move green iron where it is needed.

• Electric arc furnaces can stay where they are, near markets and supply chains.

• BF-BOFs can be preloaded with up to 30% green iron and cofired with hydrogen until the end of their kiln lives

• Eventually primary steel could all be run through DRI and EAFs, with iron being reduced and traded globally

• Eventually, when there is lots of clean electricity and power capacity, modular molten oxide furnaces can take over to supplement recycling, which should eventually dominate.

• Places like Europe and China could import reduced iron from Brazil, Australia, South Africa, etc. and eventually run almost only electric arc furnaces for primary steel.
Summary
“We can do it, but time is of the essence”

- Decarbonisation of global steel manufacturing by 2050 is technologically feasible using high TRL technologies.
- This requires all new facilities & retrofits are near zero emission by latest the early 2030s. If this is delayed early retirements will become necessary.
- China has a key role to play because of the BF-BOF capacity built ~1995-2015, 54% of global. This capacity is coming due for retrofit.
- Global innovation & commercialization programs, including private & public green procurement & lead market contracting, will be needed to make sure technologies are ready to replace older facilities from the late 2020s onward.
- Sufficient usable scrap or usable iron ore must be available.
- The scale of investment is VERY large, but has been accomplished in the past.
- The varying distribution of resources (i.e., scrap, carbon storage locations, renewable generation) means regions have varying opportunities, with different infrastructure needs.
Detailed results for countries and standard groupings (EU, G-7, G20) are downloadable available at Netzerosteel.org

Please send questions to:
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Global production costs by technology by large region
Global CAPEX by technology by large region
But what about cost per tonne (1)

- This is **not** an optimization exercise. Technology uptake is based on technical possibility and aggressive innovation and uptake policies in China and globally.

- Estimates of additional costs per tonne wildly differ, mostly based on varying electricity prices and CCS costs, but range from +20 to +70% for >=-90% reductions.

- This would only increase vehicle, bridge or building costs by +1-2%. Nationally appropriate means for risk & cost pass through must be found.

Fan & Friedman 2021 have high HDRI vs CCS, but really high electricity prices ($0.12/kWh)
### Existing Iron & Steel Facilities Included in Model  
(Additional slide for questions)

- Start with GEM Database facilities (only facilities > 1 MT of capacity)
  - 2.0 Gt of crude steel capacity in 2019, 67 countries, 622 facilities
  - Estimate of 1.6 Gt of 2019 production / 86% of global

- Cross referenced with GIDS Database, country level production identified by the Worldsteel Association and OECD national capacity database to identify remaining 14% of global production:
  - 27 additional countries (94 total) with reported production and/or capacity
  - Estimate of 213 additional facilities (mostly smaller EAF) - based on average regional operating characteristics of facilities and spatially allocated near existing production or in major country industry centres.

- Additional 39 countries are also seeded in the model for future production based on scrap availability and national demand for steel.
So where are we trying to get to?
Steel in a global net zero GHG circular economy

- Demand!
  - Determinants: population, income per capita, regs, urban planning, culture, need for vehicles, buildings, infrastructure

- Production decarbonization
- Use markets and institutions
- Recycling

Variable electricity demand

Molten oxide electrolysis -> EAF

Hydrogen direct reduced iron -> EAF

Source: Fischedick et al 2014 JCP